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BODY HEAT LOSS IN DIVING

To say that diving is cold work is not news. What is new is the severity of the thermal problem in deep excursion dives from a diving bell or habitat. A diver working from the surface expects to be chilled, and if the water is extremely cold he may need hot water in free flooding suits. But in deep saturation diving, where the water is always cold -- 5 to 10 C(41 to 50 F) -- a diver badly needs a well-insulated suit and supplemental heat, neither of which is fully available yet. In such deep dives, not only is there direct heat loss from the body to the water, but respiratory heat loss is a major drain. If a man gets in trouble he is terribly remote from topside help. To make matters worse, the bell is not an ideal place to rewarm, since the highly convective gas environment appears to drain body heat despite temperatures that feel comfortable. An unheated bell at depth is almost as severe a cold exposure as being in the water around it -- again because of the highly convective character of the hyperbaric gas.

At the surface, a man normally dives once a day, and the rewarming that starts with a hot shower actually continues for many hours as he shivers, eats hot food, exercises, and later sleeps. In the present era of saturation diving, it has been common to ask for more than one dive a day, since there is no long decompression schedule to endure. But how can a diver, or a trained observer for that matter, tell if rewarming is complete? To start a new dive with lowered body temperatures, or more precisely, at a particular value of lowered body heat content, means reaching sooner the penalties of being severely cold: poor performance, lethargy, and confusion. Physiological tolerance limits and performance limits in severe cold exposure appear when a given amount of heat is lost; thus, to start a cold exposure with a heat deficit brings the man to tolerance that much sooner.

Let us be clear that we are talking about major body heat, not just cold hands and feet or brief shivering. The physiologist usually thinks of cold exposure in terms of body responses -- vasconstriction and shivering. In cold water, these responses are often too feeble to make much difference. The diver is virtually helpless, physiologically, while heat drains away until some tolerance point is reached.

Research in cold water exposure has usually been related to the abrupt and severe exposure of shipwreck survival victims or downed aviators. There are also studies of how long-distance swimmers manage in cold water, of thermoregulation in resting or midly active nude men in warm to cool water (38 to 24C), and of the thermoregulation of

Korean women who dive for pearls in cold water. These studies, plus our basic knowledge of the physiological response to cold, are a beginning. There is precious little in the open literature that relates to the thermal physiology of underwater swimming and diving, where men wear protective clothing to attenuate the cold exposure.

We believe that change in body heat content is the central problem, and this hard-to-measure quantity is what we have studied. Defining loss of body heat from noncompensable cold exposure in diving can be as fruitful as was the study of heat storage in noncompensable heat exposure. For example, one does not expect a man working in a 70 C(160 F) room to be able to compensate by sweating. He has to stop when too many calories are stored (about 200 kcal), or he will collapse; performance deteriorates at about 3/4 of this amount of storage. Neither would one expect a man who loses heat as fast as a diver working in a 50% effective wetsuit to be able to compensate by shivering. He must stop when he has lost perhaps 200 kcal, or risk a lethal accident from poor motor control and poor judgment. A man at 400 to 1000 feet must have his wits about him, and not be severely cold.

In several types of experiments we have studied body heat loss using our suit calorimeter to quantify the heat loss. Exposures have ranged from poorly insulated dry suits in cold water to nude exposures in a bath calorimeter. In many experiments, the suit calorimeter was used as a controlled environment which could both extract heat or deliver heat (during rewarming), counting calories all the way. Net heat loss was computed from the difference between metabolic heat production and gross heat loss to the suit.

Our laboratory research was designed to simulate the kind of cold exposure divers encounter. A principal goal was to relate heat loss and change in body temperature, at both the skin surface and the core, because temperature measurements are possible in diving operations but heat loss measurements are not. The relationship has turned out to be extremely complex.

From our laboratory research, we can now estimate such practical and valuable information as: how much heat is lost by an underwater swimmer at various water temperatures; how much body heat loss is critical under different circumstances; how well rewarming procedures restore body heat; how dangerous it is when a man starts a new dive carrying a heat debt from a preceding one. Estimation is based on operating a mathematical model of body heat loss.

In the course of this study we have asked ourselves the following questions:

1. How do we measure body heat loss? A change in body heat content is generally judged from measuring the change in mean body temperature. Can we measure mean body temperature in people in cold water?

2. How much heat loss is critical? Is a debt of 100, 200, or 300 kcal the physiological limit?

3. Once a diver is cold, how does he best rewarm?

4. How does a diver know when he has rewarmed enough?

5. If a man must dive again, must he be back to normal heat before doing so? How much heat debt from the previous dive is important?

We do not have complete answers, but considerable progress has been made. This report will first summarize seven sets of experiments in cold exposure, then indicate the nature of the model which unifies the data obtained. It will describe a secondary interest in the weight loss of hyperbaric environments, and it will list additional activites undertaken. A list of publications which have resulted during the course of this contract concludes the report.

Summary of Several Series of Experiments in Cold Exposure

The seven series of experiments in cold exposure are identified in the following table, which shows how many subjects and how many experiments were involved in each. A general summary of the data was given in Webb, et al.(1979).

Number of Subjects and Experiments in the Several Series in Cold Exposure

	Number of Subjects	Number of Experiments
Series I Light dry suit in water	3	9
Series II Nude in air	6	7
Series III Rapid suit cooling	3	9
Series IV Steady state suit cooling	7	38
Series V Long slow suit cooling	3	8
Series IV Nude in bath calorimeter	4	16
Series VII Nude in water, head under (model verification)	3	15

Plus miscellaneous exploratory experiments, experiments with incomplete data, suit cooling tests, etc.

Series I

To get our feet wet, as it were, we began the project by studying three men clothed in lightweight diver's dress who exercised by swimming against a trapeze underwater at water temperatures of 5, 10, and 15 C. Prior to the dive, each subject had a heat balance calorimetrically established while he sat quietly in our environmental chamber for approximately two hours. The time of day was chosen so that a heat balance could be obtained in terms of each subject's diurnal cycle of heat production and heat loss. Following the cold exposure, which lasted either one hour, or a shorter time if the cold became intolerable, he was returned to the environmental chamber and rewarmed calorimetrically. The rewarming proceeded until the predive heat balance conditions were reestablished. Throughout this experimental day, many temperatures were monitored: three core temperatures -- rectal (T_{re}); auditory canal (T_{ac}); and esophageal (T_{es}); nine skin temperatures; plus a separate array of four skin temperature thermistors for determining continuous mean skin temperature; two subcutaneous temperatures; and muscle temperatures sampled by a needle probe at significant stages in the experiment.

Major findings were reported in articles which stressed the nature of rewarming as it had been observed, and also gave data on the various levels of heat loss in these men when they had reached their tolerance limits for cold (Webb, 1973, a and b).

Series II

Because we were interested in trying to explore the concept of body core and shell, which are two theoretically separate thermal zones of the body, we studied six subjects, including the three above, at rest and nude in the environmental chamber where the air temperatures were maintained at comfortable, warm, and cool levels of 27, 45, and 15 C respectively. Temperature data throughout these experiments were similar but more extensive than those taken in the dive: three core temperatures; 16 skin temperatures and a mean skin temperature; six subcutaneous temperatures; and muscle temperatures at a depth of 2 and 4 cm in two different sites. All of these temperature data were monitored continuously during the six hours or so of exposure to the three environments. Unfortunately, the temperature data did not clearly distinguish a shell temperature, nor the core-shell gradients one would need for mathematical descriptions of internal heat transfer. We would have needed even more probes, many of them more deeply placed -- and we had already exceeded the limits of discomfort in these very cooperative subjects. So, while this interesting series was never reported as such, we used the insights gained in later formulations of internal heat flows during cooling.

Series III

In this series, the main line of investigation was a study of the effects of body cooling, using the water cooling garment as the cooling medium instead of the cold water tank used in Series I. This allowed a direct measurement of heat extracted during the cooling period. Rewarming with the garment was done with caloric accounting, as before. In six experiments on resting subjects, cooling was carried to the voluntary tolerance point, which took 80 to 120 minutes, and produced decreases in body heat content in the range of 166 to 360 kcals. We were not clear whether these experiments had reproducible end-points. Subjects seemed to be able to make themselves go longer on a second or third trial, hence lost more heat.

In these voluntary tolerance runs, we did not see much reduction in internal body temperatures (rectal or esophageal), which was surprising. In our earlier studies of men in the cold water tank, we thought it was the vigorous swimming work during the immersion which kept core temperatures high as 200 to 300 kcal were lost. This series in the suit was done with men seated at rest, so exercise was not the reason that core temperatures stayed high. However, there was a strong shivering response, which had the same effect as exercise. By the end of the cold exposure, heat production had increased enough to nearly equal the rate of heat loss -- and the subjects were fatigued. We began to realize that we needed even better cooling garments in order to shorten the exposures and to be able to overwhelm the shivering metabolism. New suit designs were devised and new garments having many cooling tubes with short flow paths were made. These came to be called "high flow suits". Several more experiments were done with rapid cooling in these suits. Results were partially reported at the 1979 annual meeting of the Aerospace Medical Association (Annis et al., 1979).

Series IV

The rationale for this series arose from our earlier experiments with the suit calorimeter. Because the early suits had limited cooling capacity, subjects reached tolerance levels of heat loss (average level 218 kcal) only after 80 to 120 minutes of cooling, which made for rather long and tiring experiments. Shivering was intense when heat production, estimated from $\dot{V}O_2$, was almost equal to heat removal, and discomfort was such that rewarming had to be started immediately following voluntary termination of cooling. Consequently, the sluggish body core temperature (rectal) continued to drop for approximately 20 to 30 minutes during the rewarming period, while the more rapidly responding skin temperature remained nearly in phase with the suit environment, and ear canal and esophageal temperatures fell in between these extremes. The fact that body temperatures were always moving made interpreting relationships between body temperatures and levels of heat loss very difficult. In order to find discrete magnitudes of change in body core temperature for known amounts of heat loss for different individuals, experiments with steady state endpoints were needed.

By using the new high flow suits, it became feasible to obtain a steady state condition with reduced body heat content. These highly efficient garments could approximate the bath calorimeter cooling rates previously described by other investigators, while at the same time retaining the precision of control necessary for our work.

Five male subjects participated in 31 experiments designed to induce and maintain specific levels of hypothermia for the purpose of observing the complete response of core temperatures. Each level of heat loss (50, 100, or 150 kcal) was controlled calorimetrically. The experiment began by removing a specific amount of body heat in excess of that being generated metabolically. Then the subject was maintained in thermal balance at the new level of lowered body heat content.

Interestingly, if shivering appeared during the cool down, it ceased the moment the calorimeter warmed up to maintain thermal balance. While this new thermal state was maintained within ± 10 kcal, the rectal temperature was allowed to seek a level and stabilize there for one hour. Once the rectal temperature became stable, it could be seen that its change was directly proportional to the change in body heat content. But it was also obvious that people react individually. It appeared that body size, surface area, and fatness all affected the result.

Results from experiment Series III and IV were reported, in part, in 1975, at the VIth Symposium on Underwater Physiology (Webb, 1978) and at the 1977 annual meeting of the Undersea Medcial Society (Webb et al., 1977A).

Series V

Because the rate of cooling seemed to influence the relationship between net heat loss and body temperature we designed the next experiments to remove heat much more slowly than before. In this series the strategy was to cool subjects gradually over a long period of time until as much heat had been lost as in previous experiments -- namely, 150 to 300 kcal. Four men were studied. They lost heat at rates of 50 to 60 kcal/hour, in exposures lasting four to eight hours. Net heat losses were 150 to 300 kcal. We were fascinated to observe that these great heat losses, slowly incurred, caused little shivering and only minor reductions in core temperature.

The long slow cooling of this series had more than academic interest. The effects appeared to be quite similar to those observed in underwater swimmers who must pass through cold water in swimmer delivery vehicles for up to six hours at a time. Multiple layers of wet suits protect them, but not perfectly, and they lose heat in the same long slow pattern -- perhaps to the same degree.

Series VI

After the long slow cooling experiments, we did a series in which heat removal happened much faster than in any previous series. Higher cooling rates than were achievable with the high flow suit were needed to enable us to relate our special experience in cold exposure to the more common experiments with nude men in cold water, yet we wanted to continue the calorimetric quantification of heat loss. Fortunately, Dr. L. Kuehn, at the Defence and Civil Institute of Environmental Medicine near Toronto, made available the bath calorimeter originally developed by A. Craig at the University of Rochester. We designed a protocol for rapid cooling in the bath calorimeter (head out of water), followed by rewarming in a sleeping bag version of our suit calorimeter, with metabolism measured throughout.

Four men served as subjects for the 16 experiments. Each man was cooled in 24 C water for an hour and in 18 C water for an hour, unless tolerance was reached sooner. The exposures were all repeated once.

Shivering and sizable decreases in rectal temperature were observed, as expected. The calorimeter showed net heat losses from 280 to 370 kcal at 18 C. Summary data are given in Annis et al.(1979).

Series VII

A set of predictive equations had been developed from the experience of the first six sets of experiments, and this seventh series was designed to test those equations. The equations predicted well enough the empirical results of the suit cooling and bath calorimeter experiments. A more severe test of the model was to ask it to predict the results of new conditions, then try them experimentally. The conditions chosen were: nude exposures in water, at 12, 20 and 28 C; subject's head under water; subjects at rest and exercising.

Three men underwent these exposures, which lasted, for the experiments at rest, one hour at 28 C, 45 to 60 minutes at 20 C, and 25 to 43 minutes at 12 C. The experiments with exercise, which involved underwater pedalling of a bicycle ergometer with a brake load of 50 W, were done at 28 and 20 C. None of the subjects volunteered to endure the 12 C exposure again.

Predictions of heat loss and change in rectal temperature for these underwater cold exposures were reasonably good. The experiments of this series are to be included as part of a planned report of the mathematical model (Troutman & Webb, 1980).

Biothermal Model of Body Heat Loss

Throughout the project it had been the intent to devise predictive equations from the experimental data. These equations were to define a biothermal model of body heat loss in diving, thus becoming a summary of the results. The model was to predict not the physiological responses to cold, which are surface vasoconstriction and shivering, but how much heat is lost and what change in core (rectal) temperature results from given exposures. Much effort was expended on multicompartment constructs of the body, but in its latest development, the model has but one core and one shell. It is, conceptually, a sphere; the model has become nonanatomical.

Significant ideas in developing the model included: the observation that thermal responses follow exponential patterns; that the rate of cooling affects the change in core temperature; that physical size of the body, its surface area and its composition (fatness) determine temperature response; and that coupling between shell and core vary with time and environmental load.

The nonanatomical spherical model has a surface which interfaces with the environment, a shell where all the mass lies, and a core with no mass. Equations predict, over time, the surface, shell, and core temperatures, mean body temperature, and net heat loss. Initially, one enters various descriptive values for body size and composition of the subject, how well he is coupled to the environment, the environmental temperature and initial compartment temperatures. The equations then solve for the various temperatures and heat loss in increments of time, e.g., 5 minutes, and curves can be drawn from these serial solutions.

Some conclusions reached:

1. Surface temperature is a poor predictor of hypothermia.

2. To relate core temperature to net heat loss one must know the dynamic response of the temperature of the shell and its variable coupling with the core.

3. In hypothermia, the core temperature is strongly affected by the rate of heat loss, and by the size of the body and its composition.

The model has been tested by having it predict thermal responses of men in conditions not previously studied experimentally, then those conditions were tried in new experiments and the results compared with the predictions. On the whole, the agreement was quite good. An early report of the model was presented in a poster session at the 1979 meeting of the Undersea Medical Society (Troutman et al., 1979). A report for the literature is being prepared (Troutman & Webb, 1980).

Weight Loss in Hyperbaric Environments

During early experience with saturation diving, it had been observed that the divers ate more than usual yet they lost weight. The weight loss had been documented several times, but the estimations of food intake were inexact. We found this story intriguing, believing it to be, if true, an expression of a thermal drain in conditions which were judged to be thermally comfortable. Therefore, we were pleased to participate in a 1200 foot saturation dive at the University of Pensylvania's Institute for Environmental Medicine. Careful daily records were kept of body weight and food intake. The four men did eat more than their activities seemed to call for; they lost weight; and yet there was no evidence from body temperature data or from metabolism measurement that they were under any thermal stress. The story had been verified, but an explanation not found (Webb, 1973c).

A second opportunity arose several years later. At the University of Hawaii a saturation dive called Hana Kai II (Hong et al., 1977) was being planned. As participants in that study, we designed an energy balance study to try to explain the phenomenon of weight loss in the face of high food intake.

To ensure that all critical quantities were directly measured, an elaborately detailed study was designed, in which all food eaten was not only weighed but all items were sampled for analysis by bomb calorimetry; the energy of urine and feces was determined by bomb calorimetry; and careful records were kept of water exchange. Metabolism was measured on all four men in 24-hour periods with an open system apparatus specially designed for the project (Troutman & Webb, 1978). Body weight was recorded daily; total body water was determined before, midway, and after the dive; and body composition was calculated from body density before and after the dive. The men ate more than they required to match daily metabolic expenditure, even at sea level pressure, yet they failed to gain weight. The explanation was not found in increased body waste, in body water loss, or in exchanges between lean body mass and fat compartments. In fact, there seemed to be just over 900 kcal/day of unaccounted for energy for the 30 days of the study. That is, there was 900 kcal/man-day of food intake that did not show up either as energy loss or as increased body heat storage (Webb et al., 1977b). The mystery remains. We wonder whether, if we had been able to use direct calorimetry to measure body heat loss, it might have shown increased heat loss despite no drop in body temperature or increased metabolism.

In fact, the measurement of energy balance during more normal circumstances is not simple. Studies made in other projects during the period of this contract, where we have used both the suit calorimeter and the apparatus for measuring metabolism simultaneously, failed to confirm that an energy balance always existed between fuel oxidized and heat loss plus work. Early data of this kind (Webb et al., 1980) and an analytical review (Webb, 1980) were prepared for publication.

these two reports, like the study of weight loss in saturation diving, challenge the comfortable convention that energy exchange is completely measurable by known techniques.

Other Activities

During the years this contract has run, the principal investigator found himself drawn into a number of activities which, while not strictly research, were pertinent to the subject matter. These activities included: several Navy sponsored research conferences (e.g., ONR-SUPSALV Workshop on Advanced Diving Technology; BuMed-ONR Technical Working Group on Biomedical Requirements, Man in the Sea - Deep Ocean; Navywide Workshop on High Pressure Biomedical Research; Conference on Medical Problems of Submarine Survivors); an Undersea Medical Society workshop on "Thermal Problems in Diving" (Webb, 1974); helping to write a "national plan" for diving research (Webb et al., 1975); a conference to define thermal limits for designers of thermal protection gear (Webb et al., 1976); two reviews of thermal problems in diving (Webb, 1975, 1976); and some conference papers which drew in part on the work of the contract (Troutman, 1976; Troutman et al., 1977; Webb et al., 1978; and Webb, 1979).

List of Publications

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